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THE EFFECT OF IMPURITIES AND STRUCTURE ON THE
TENSILE TRANSITION TEMPERATURE OF CHROMIUM

by

B. C. Allen, D. J. Maykuth, and R. I. Jaffee

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ABSTRACT

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Wrought unalloyed iodide chromium, containing 39 to 95 parts per million total interstitials, has a tensile transition temperature of -15 C. Recrystallizing at 1100 C causes the transition to rise to 90-390 C, depending on the purity, grain size, and cooling rate after annealing.

At about the 100 ppm level, individual additions of carbon or nitrogen raise the transition of both wrought and recrystallized chromium by as much as 210 C, while oxygen has a lesser effect, and sulfur essentially no effect. High transition temperatures are exhibited by recrystallized and quenched chromium, and appear to be associated with the amount and distribution of interstitials. The latter can be either in solid solution or in the form of precipitates within the grains or at the grain boundaries. Quench hardening in chromium is primarily caused by nitrogen. The hardness, recrystallization, and grain growth behavior of chromium with and without impurity additions were also investigated.

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Introduction

Because of low density and good oxidation resistance, chromium-base alloys are potentially useful for elevated-temperature applications. The main deterrent to the use of chromium in structural applications is its lack of low-temperature ductility, especially in the recrystallized condition. Accumulated evidence has shown that the ductility of chromium is sensitive to purity.

The objective of the current study was to determine the effect of common nonmetallic impurities on the tensile properties of high purity chromium. The separate effects of carbon, oxygen, nitrogen, and sulfur additions on the ductile-to-brittle transition were evaluated for wrought and recrystallized material after various cooling rates.

Experimental Work

Unalloyed iodide chromium and seven impurity alloys containing individual carbon, oxygen, nitrogen, or sulfur additions were prepared in rod form. Nominal additions were 100 ppm carbon, nitrogen,

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and sulfur, and 100-500 ppm oxygen. The additions were about a factor
of ten greater than the residual amounts in the unalloyed material. The
seven alloys and two unalloyed compositions were consolidated into four-
pound ingots by conventional consumable arc melting of pressed and welded
electrodes under 0.5 atmosphere of helium. Impurity additions were made
to the electrode in the form of crushed master alloys. The impurity
alloys were double melted to improve homogeneity. The ingots were broken
down by extrusion at 1200 C in evacuated steel cans at a reduction ratio
of 18:1, using a molten borosilicate glass lubricant and a ram speed of
30 inches per minute. The cans were removed by acid pickling, and the
chromium core ground free of surface undulations. Cut lengths were
sheathed in mild steel and swaged at 900 C until the core was about 1/4
inch in diameter.

Two additional 15-pound ingots of unalloyed chromium (ICr-3,
ICr-4) were prepared by arc melting and broken down by 26:1 extrusion at
1250 C without a steel can. The billet was lubricated and protected from
contamination by a coating of molten glass. The resulting extrusion was
then sheath swaged as described previously.

Representative chemical analyses of each of the materials,
after removal of a 10-mil surface layer are presented in Table 1. The
results indicate this amount of surface cleanup was sufficient to remove
the contaminated metal resulting from consolidation and fabrication.
The impurity additions approximated the desired levels.

Miniature buttonhead tensile specimens were ground from the
as-swaged rod according to the profile in Figure 1. Batches of speci-
mens were annealed in argon-filled quartz capsules at 800 or 1100 C,
followed by an oil quench or furnace cool. About 2.5 mils of surface

TABLE 1. ANALYSES OF IODIDE CHROMIUM AND SEVEN IMPURITY ALLOYS

Parts per Million by Weight

Alloy	Interstitials					Metallics(e)											
	C(a)	O(b)	N(c)	H(b)	S(d)	Al	Ca	Cu	Fe	Mg	Mn	Mo	Ni	Si	Ti	V	Zr
As-received iodide chromium crystals	10	8	<3	0.2	10	1	3	2	50-200	1	<0.3	<1	2	<20	<1	2	<2
ICr-1 rod	48	32	14	<0.8	6	<3	3	10	45	1	<0.3	<3	4	10	<1	<3	<2
ICr-2 rod	44	24	10	<0.7	9	4	3	1	60	1	<0.3	<3	4	10	3	<3	<2
ICr-3 rod	35	48	12	0.5	--	5	4	2	75	0.5	<0.3	<3	4	<20	<1	4	<3
ICr-4 rod	15	20	2	1.8	--	--	--	--	~100	--	--	--	--	--	--	--	--
C-1 rod	150	27	10	<0.7	13	--	--	--	~50	--	--	--	--	--	--	--	--
O-1 rod	40	128	13	<0.6	11	--	--	--	~50	--	--	--	--	--	--	--	--
O-2 rod	54	545	12	1	9	--	--	--	~50	--	--	--	--	--	--	--	--
N-1 rod	--	--	145	--	--	--	--	--	~50	--	--	--	--	--	--	--	--
N-2 rod	--	--	80	--	--	--	--	--	~50	--	--	--	--	--	--	--	--
N-3 rod	48	62	66	0.8	--	--	--	--	~100	--	--	--	--	--	--	--	--
S-1 rod	83	62	25	<0.8	90	--	--	--	~50	--	--	--	--	--	--	--	--

(a) Combustion-conductimetric, ±5 ppm.
(b) Vacuum fusion, ±6 ppm oxygen, ±0.7 ppm hydrogen.
(c) Micro-Kjeldahl, ±5 ppm.
(d) Distillation, ±5 ppm.
(e) Concentration spectrographic.
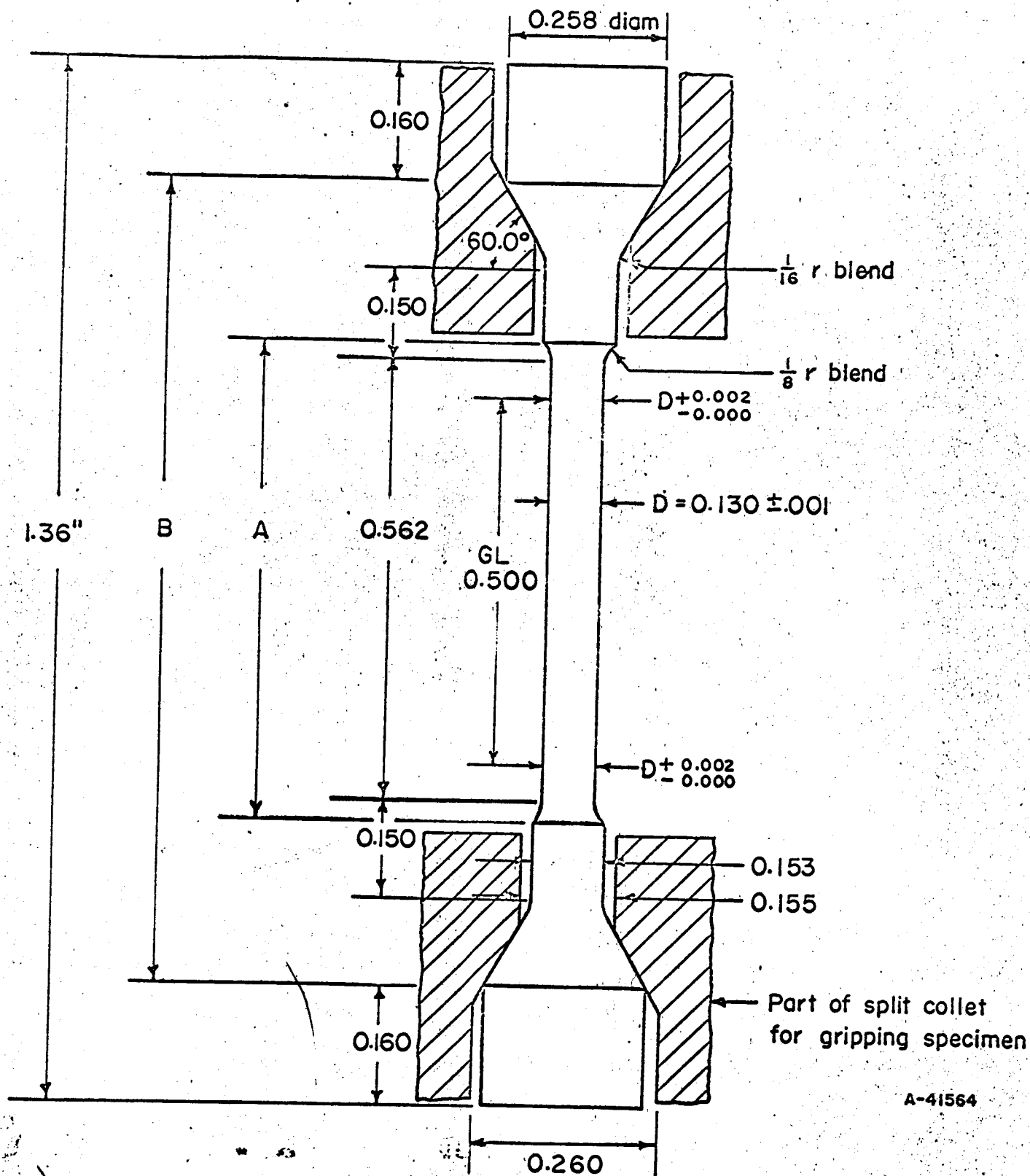
FIGURE 1. DESIGN OF MINIATURE TENSILE SPECIMEN
PRIOR TO ELECTROPOLISHING

were removed by electropolishing in 10:1 acetic acid-perchloric acid at 5 amp/in.^{2} at 50 C. Check analyses indicated essentially no carbon, oxygen, nitrogen, or silicon pickup from annealing and quenching.

The tensile specimens were held in Inconel X grips equipped with a loop-type extensometer. The unit could be used for low as well as elevated temperature tests on standard tensile machines. Subambient temperatures were obtained with dry ice-methyl alcohol mixtures and elevated temperatures in air up to 625 C by a resistance furnace surrounding the specimen. All load-elongation curves were recorded autographically. To avoid notch effects, no gage marks were put on the specimens. Since the extensometer readings gave elongations (ΔB, Figure 1) over the entire reduced section and shoulders, a small correction was made to obtain elongations in the 0.5 inch gage section. This correction was <0.05 ΔB as determined experimentally on six wrought ICr-1 specimens pulled at room temperature. The strain rate was estimated from crosshead speed.

Results and Discussion

Hardness

The room-temperature hardness of chromium and the impurity alloys was determined in various stages of fabrication. The hardnesses of all of these materials were in the 137-145 VHN range after arc melting and changed insignificantly to 131-140 VHN after extruding. Thus, all materials were essentially in the annealed condition with the hardness apparently unaffected by the impurity additions.

After swaging to an 80 per cent reduction in area, significant differences in hardness were noted as indicated in Figure 2. The unalloyed chromium had a hardness of 160-175 VHN, the alloys containing oxygen and carbon 180-200 VHN, and the alloys containing 25-145 ppm nitrogen 200-250 VHN. Furthermore, the alloys containing nitrogen were difficult to swage and cracked severely. It appears that nitrogen caused hardening at the swaging temperature of 900 C and was responsible for this behavior. The adverse effects of nitrogen on fabricability of chromium are in agreement with those reported by Wain, et al.,[1].

Vacuum annealing the wrought material for one hour up to 900 C caused some recovery while annealing at 1000-1100 C followed by a cooling rate of about 100 C/min caused the hardness to drop to the 130-140 VHN range. As the annealing temperature was raised to 1400 C, the values fell to 125-130 VHN, approximating the hardness of the starting crystals of 129 VHN.

On the basis of reported hardening and reduction in ductility caused by quenching chromium[2,3,4] the effect of cooling rate from 800 and 1100 C on hardness was investigated. Quenching from the recovery annealing temperature of 800 C resulted in only minor hardness changes which did not appear to be connected with composition. The estimated rates used in cooling from 1100 C to black heat were slow (3 C/min), moderate (100 C/min), and quench (>1000 C/min). The slow and moderate cooling rates from 1100 C had only a minor effect on the hardness of unalloyed chromium and the impurity alloys. However, quenching from 1100 C caused significant hardening in the alloys containing over 15 ppm nitrogen, but not in those containing oxygen or carbon additions. This behavior was also noted in nitrogen-dosed chromium containing up to
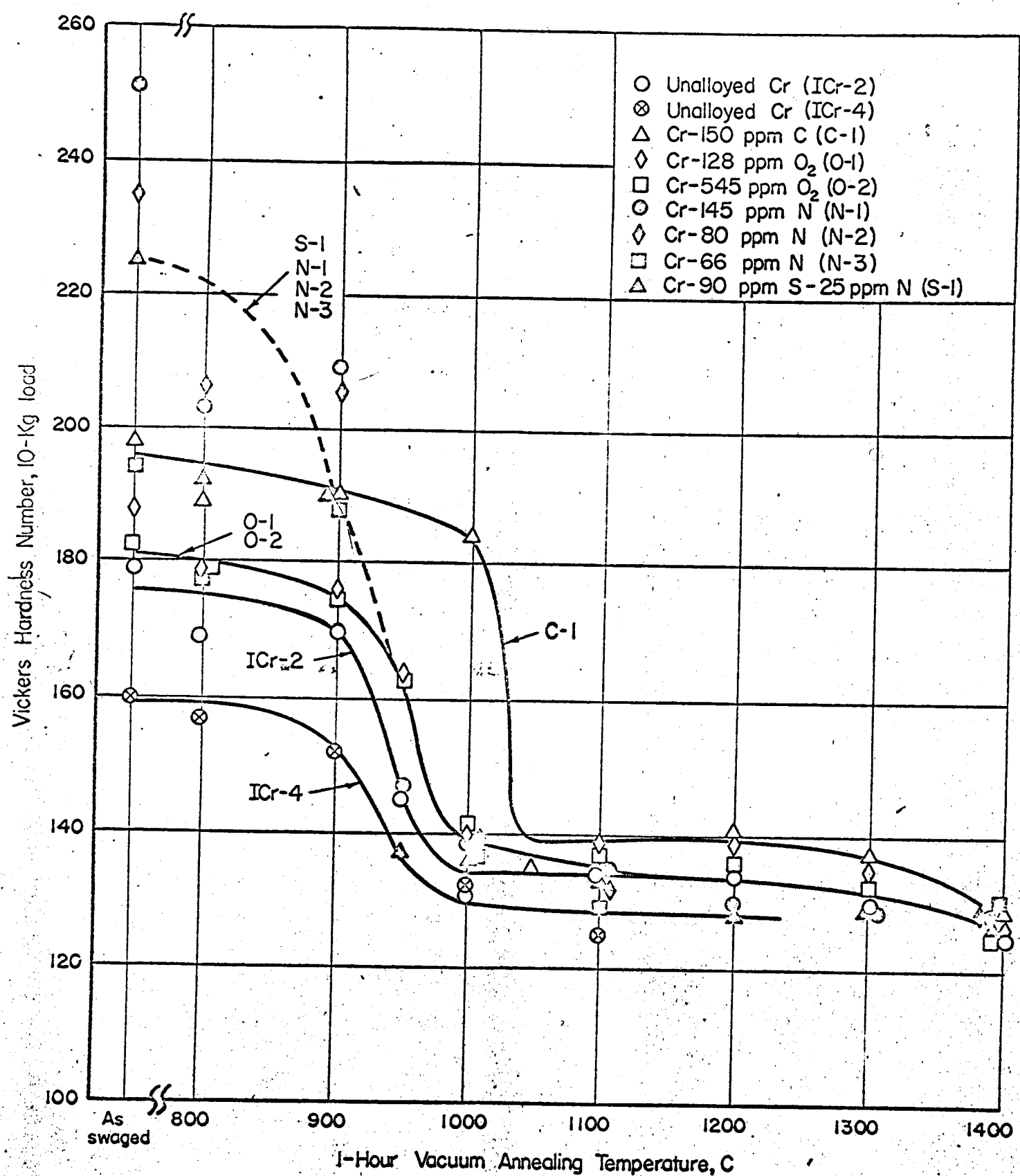
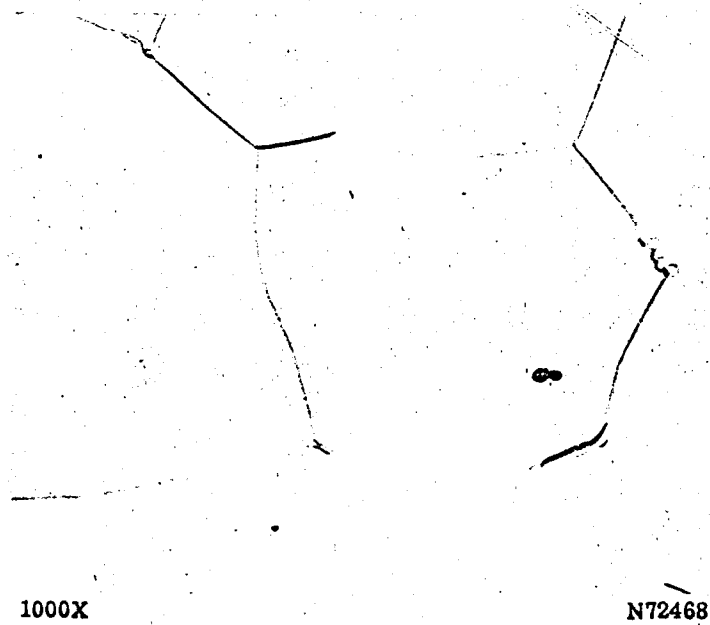FIGURE 2. SOFTENING CURVES OF IODIDE CHROMIUM AND IMPURITY ALLOYS

360 ppm nitrogen after quenching from 1100 C, and in rapidly cooled arc-cast buttons[5]. All of these data are summarized in Figure 3, which indicates that the degree of quench hardening obtained can be correlated to the nitrogen content of the chromium. These data suggest that increasing nitrogen in amounts to about 30 ppm results in a rapid increase in quenched hardness to a value around 158 VHN. Nitrogen additions in greater amounts continue to raise the quenched hardness, though at a somewhat reduced rate.

The quench hardening caused by nitrogen in chromium can be rationalized in terms of its distribution. As shown in Figure 4a, the nitrogen in slow-cooled chromium containing 145 ppm nitrogen is distributed in the form of coarse grain boundary nitrides. Nitrogen in quenched material, Figure 4b, is in a much finer form, either in super-saturated solid solution and/or as a fine Widmanstätten precipitate. The latter form has been identified as an etching effect or indications of dislocation decoration with nitrogen[2,6]. Further evidence suggests that the hardening is primarily associated with nitrogen in solid solution since little second phase was observed in quenched alloys containing 66 and 80 ppm nitrogen which had similar hardnesses. The break in the curve of Figure 2 suggests a maximum of 30 ppm nitrogen in solution and the balance in precipitates. On quenching there was little time available for diffusion, which caused the nitrogen to remain finely dispersed and cause hardening. Since nitrogen solubility is highly temperature-dependent[7], nitrogen in the slow-cooled material apparently had time to diffuse and form a coarse grain boundary precipitate, leaving very little (<10 ppm) in solution to cause hardening.
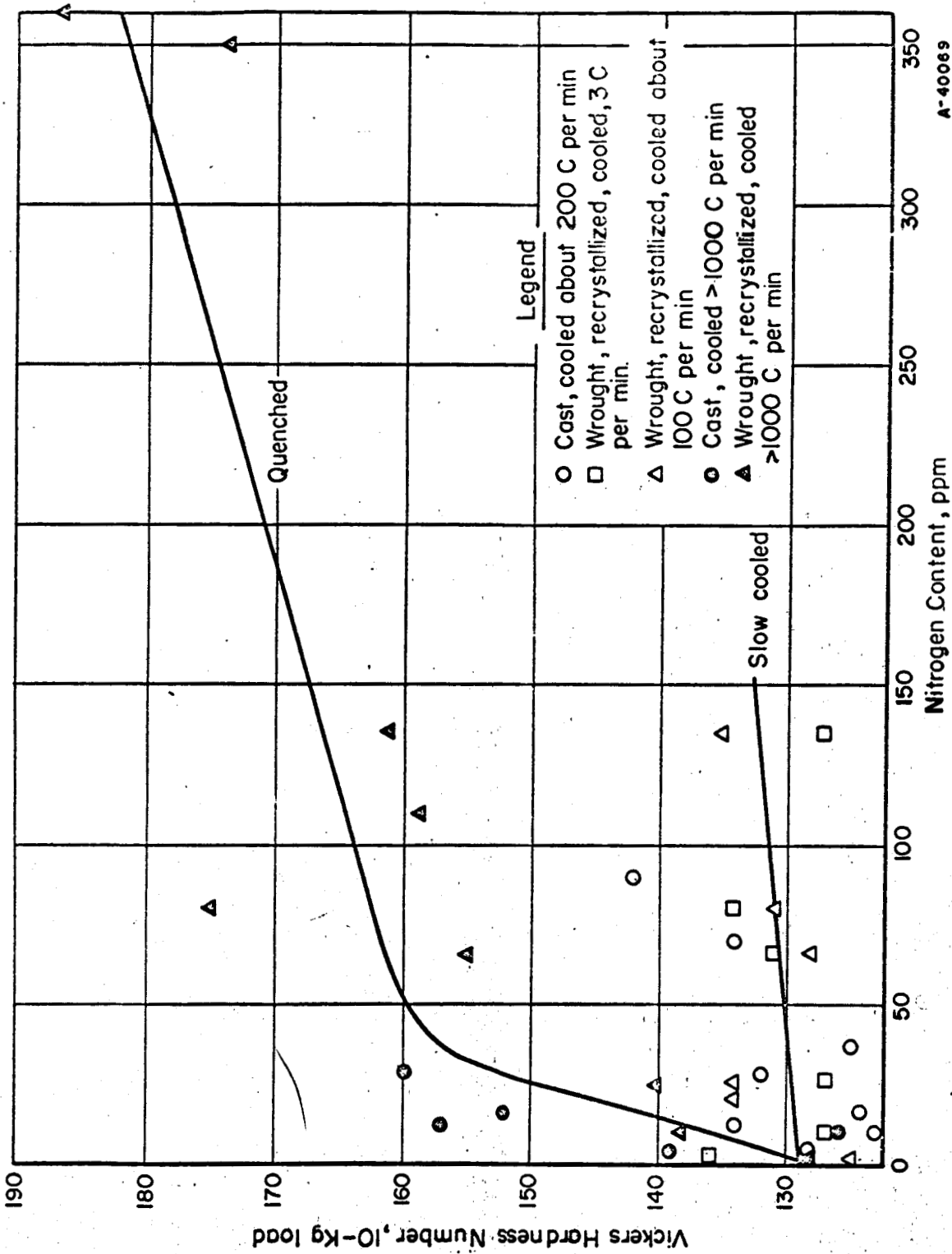
FIGURE 3. EFFECT OF NITROGEN AND COOLING RATE ON THE ROOM-TEMPERATURE HARDNESS OF CHROMIUM

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Legend

○ Cast, cooled about 200 C per min
□ Wrought, recrystallized, cooled, 3 C per min.
△ Wrought, recrystallized, cooled about 100 C per min
◉ Cast, cooled >1000 C per min
▲ Wrought, recrystallized, cooled >1000 C per min

Quenched

Slow cooled

Nitrogen Content, ppm

Vickers Hardness Number, 10-kg load

1000X   N72468

a. Furnace Cooled (3C/Min)

1000X   N72469
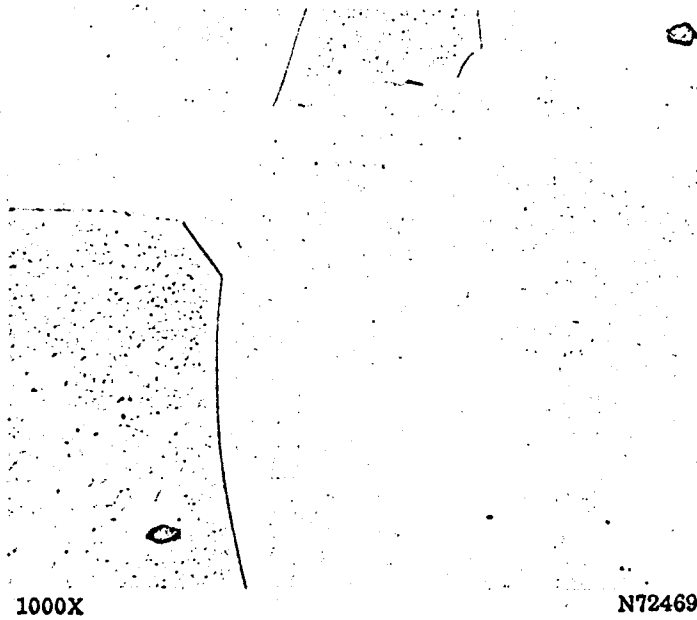
b. Oil Quenched (>1000 C/Min)

FIGURE 4. LONGITUDINAL MICROSTRUCTURES OF WROUGHT AND RECRYSTALLIZED
Cr-145 PPM N (N-1)

10 per cent oxalic acid-electrolytic etch.

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Recrystallization

The recrystallization behavior of chromium and impurity alloys with 80 per cent warm work at 900 C was investigated. As indicated in Figure 2, all of the chromium alloys softened appreciably after annealing at 950 to 1050 C. Microstructures of these materials, illustrated in Figure 5, as well as back-reflection Laue X-ray analysis showed this softening to be associated with recrystallization. Complete elimination of the worked structure was associated with leveling out of the softening curve with increasing annealing temperature.

All the alloys except Cr-150 ppm carbon showed 10-90 per cent recrystallization after annealing one hour at 950 C, and essentially no residual work at 1000 C and above. Thus, the minimum temperature for complete recrystallization in these materials was estimated at 975 C. In contrast, the 150 ppm carbon alloy exhibited a completely worked structure at 1000 C and a completely recrystallized one after annealing at 1050 C. The results indicate that at the levels investigated, oxygen, nitrogen, and sulfur have little effect on the recrystallization temperature of chromium, while carbon increases it slightly. The 60 and 100 ppm iron levels in the unalloyed chromium samples did not appear to affect recrystallization behavior. At higher levels 5000 ppm iron plus 3000 ppm nickel raise the recrystallization temperature of chromium by about 200 C[8].

It is of interest to note that the effects of interstitial impurities on the recrystallization temperature of chromium are similar to those observed in tungsten[9]. Again only carbon appears to exert a noticeable effect.

100X   N72113   a. 800 C

100X   N72115   b. 950 C
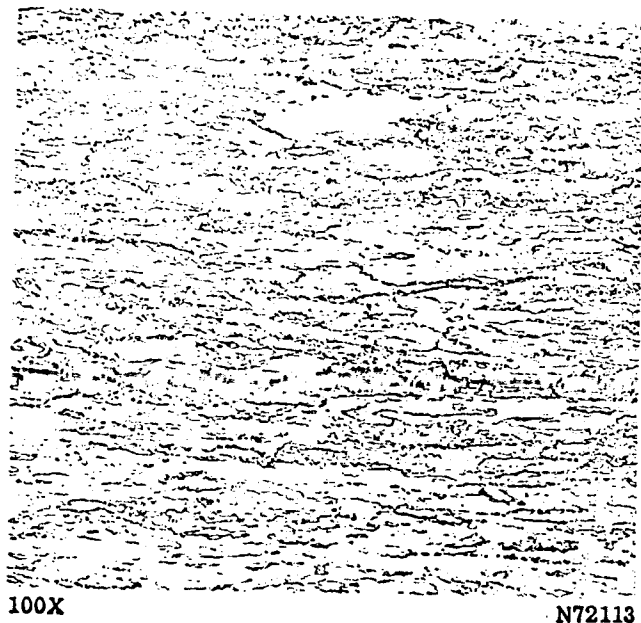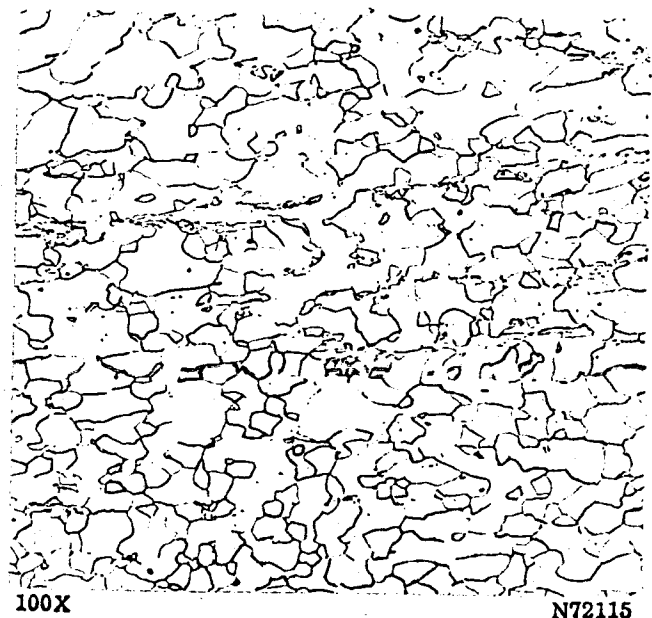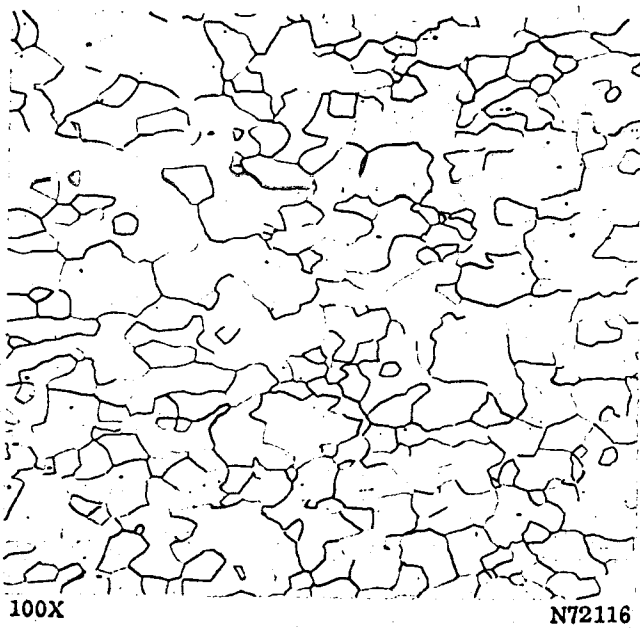
100X   N72116   c. 1000 C; Grain Diameter: 0.031 mm

100X   N72120   d. 1400 C; Grain Diameter: 0.083 mm

FIGURE 5. LONGITUDINAL MICROSTRUCTURES OF WROUGHT AND ANNEALED UNALLOYED IODIDE
CHROMIUM (ICr-2)

10 per cent oxalic acid-electrolytic etch.

Grain Size

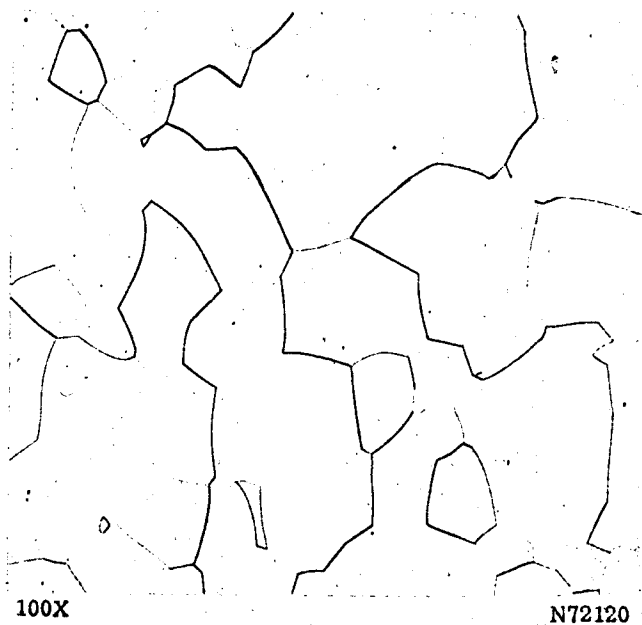Chromium and the impurity alloys generally exhibited normal grain-size behavior. The larger arc-cast ingots of unalloyed chromium had an average grain diameter of 5 mm, the smaller 3 mm, and the impurity alloys 1-2 mm. Extrusion reduced the grain size in all materials to an equiaxed size of about 0.03 mm, which was essentially the same size in the worked and 1100 C-recrystallized material. The only exceptions were the purer unalloyed chromium, ICr-3 and ICr-4, which apparently recovered somewhat during swaging at 900 C and gave a mixed recrystallized grain size of 0.08 mm along with some grains as large as 1 mm. The carbon-containing alloy had the smallest recrystallized grain sizes of about 0.01 mm as indicated in Figure 6.

Annealing between 1200 and 1400 C generally caused rapid grain growth. The rate was highest for Cr-90 ppm sulfur, possibly because of a redistribution of sulfur or solution of sulfide inclusions as the temperature was raised, thereby promoting accelerated growth. The grain size of Cr-145 ppm nitrogen alloy stayed essentially constant at 0.045 mm and indicated an inhibiting effect of nitrogen.

Transition Temperature Behavior of Unalloyed Chromium

Wrought and recovered unalloyed iodide chromium with 80 per cent warm work and <100 ppm total interstitials and a maximum of 10 ppm nitrogen showed appreciable room-temperature ductility, i.e., about 80 per cent reduction in area and 50 per cent elongation in 1/2 inch at a strain rate of 2 per cent per minute. Ductilities at other temperatures ranged from 0 to 90 per cent reduction in area as indicated in Figure 7.
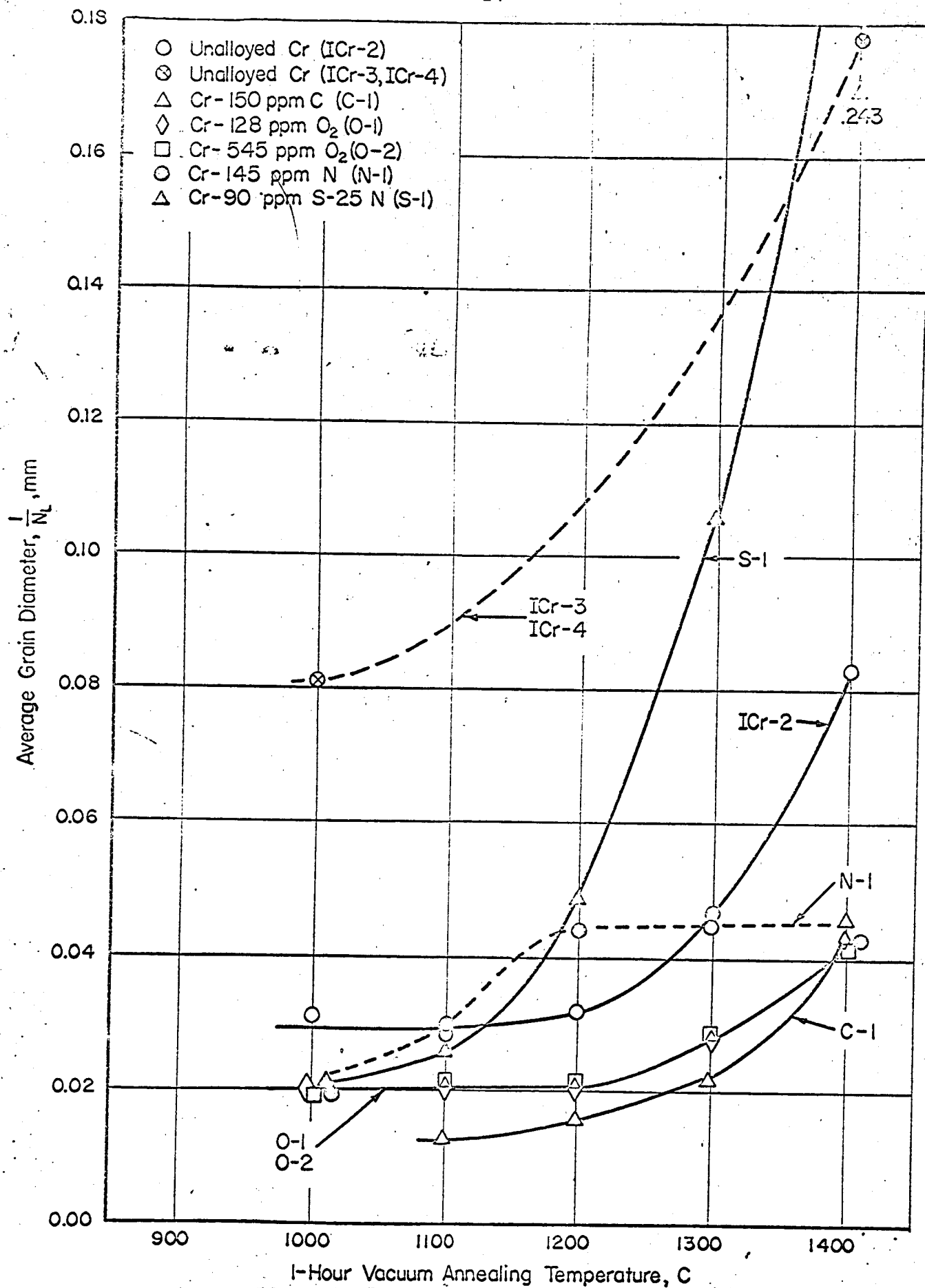
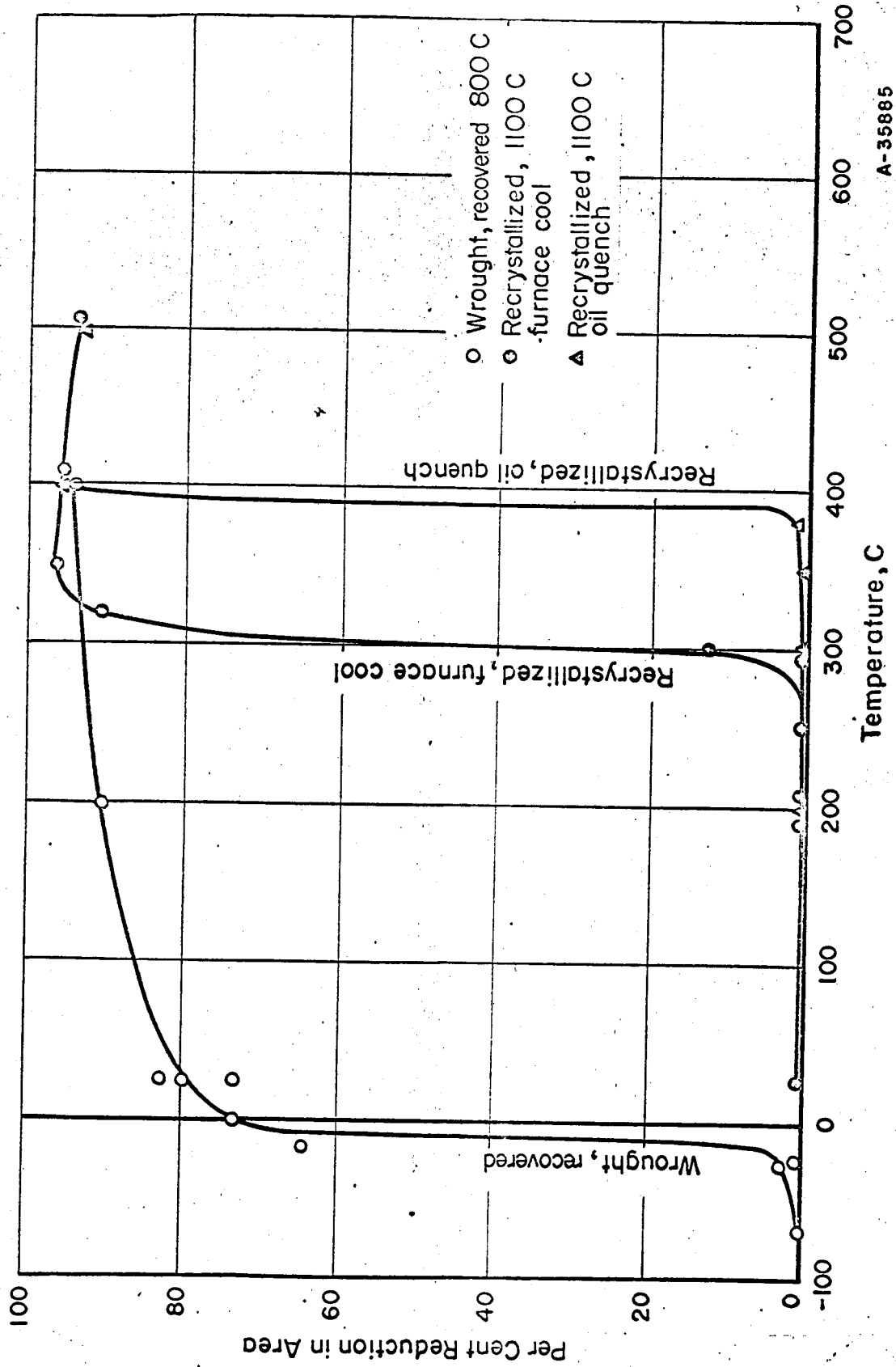FIGURE 6. GRAIN GROWTH OF IODIDE CHROMIUM AND IMPURITY ALLOYS

FIGURE 7. TENSILE DUCTILITY OF UNALLOYED IODIDE CHROMIUM (ICr-2)
AS A FUNCTION OF TEMPERATURE

A-35885

With the transition from ductile to brittle behavior estimated as the temperature at which the reduction in area decreased to one-half the maximum value, the transition for wrought chromium was about -15 C. This result compares with bend transition temperatures reported in the -25 to -75 C range at comparable strain rates[1,10].

Ductilities of wrought unalloyed chromium were measured under a variety of conditions indicated in Table 2 to determine their effects on transition temperature. Increasing the strain rate from 2 to 200 per cent per minute had no significant effect on room-temperature tensile ductility although the ultimate strength was increased from 75 ksi to 84 ksi. This insensitivity of ductility to a 100-fold change in strain rate is consistent with published results[11] for bend transition behavior of sintered chromium. Also, variations in cooling rates from 3 C/min to oil quenching after recovering at 800 C had <40 C effect on the transition. As-swaged chromium also had room-temperature ductility. The ductility of chromium specimens was insensitive to surface removal by electropolishing as long as >1 mil of surface including grinding marks were removed. Removal of <1 mil or roughening the surface caused erratic embrittlement and >40 C rise in transition temperature. Similar indications of the notch sensitivity of chromium have been reported by others with regard to tensile[12] and bend[1,10,12] ductility.

The transition temperature results for unalloyed chromium, ICr-2, ICr-3, and ICr-4, are presented in Table 3. As recovered, each of the types gave the same transition of -15 C. There appeared no significant effect of varying carbon from 15-44 ppm, oxygen from 20-48 ppm, or nitrogen from 2-12 ppm as associated with the fabrication sequence used.

TABLE 2. EFFECT OF VARIOUS CONDITIONS ON THE ROOM-
TEMPERATURE TENSILE DUCTILITY OF WROUGHT
UNALLOYED IODIDE CHROMIUM

Strain Rate, per cent per minute	Thickness of Surface Removed by Electropolishing, mils	Reduction in Area, per cent	Ultimate Tensile Strength, 1000 psi
ICr-2, As Swaged			
2	2.5	75.0	63.9
ICr-1 Recovered 1 Hour 600 C, Cooled 100 C/min			
2	1.1	78.6	68.9
2	3.0	80.0	75.1
20	2.5	77.3	82.7
200	2.5	76.7	84.1
2	2.1[a]	70.2	75.0
2	2.1[a]	5.0	72.9
ICr-2 Recovered 1 Hour 800 C, Cooled 3 C/min			
2	2.5	79.8	64.9
2	0.05	0.5	64.2
ICr-2 Recovered 1 Hour 800 C, Oil Quenched			
2	2.7	60.6	64.5

(a) Roughened transversely to mount strain gages.

TABLE 3. EFFECT OF PURITY AND STRUCTURE ON THE TENSILE TRANSITION TEMPERATURE OF IODIDE CHROMIUM

								Tensile Transition Temperature, C		
							Wrought and Recovery	Recrystallized 1 Hour at 1100 C		
		Impurity Content, ppm					Annealed 1 Hour at 800 C,	Quenched	Furnace Cooled	Average Grain
Alloy	C	O	N	H	S	Fe	Furnace Cooled	>1000 C/Min	3 C/Min	Diameter, mm
ICr-2	44	24	10	<0.7	9	60	-15	390	300	0.029
ICr-3	35	48	12	0.5	--	75	-15	230	90	0.08
ICr-4	15	20	2	1.8	--	~100	-15	230	--	0.08
C-1	150	27	10	<0.7	13	~50	150	600	470	0.013
O-1	40	128	13	<0.6	11	~50	20	590	400	0.020
O-2	54	545	12	1	9	~50	30	600	390	0.022
N-3	48	62	66	0.8	--	~100	160	490	290	0.025
S-1	83	62	25	<0.8	90	~50	180	550	420	0.026

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The effect of recrystallization and cooling rate on the transition was determined. Since traces of residual work greatly lower the transition[1,12], a conservative annealing temperature of 1100 C was chosen to insure complete recrystallization. Recrystallizing caused a rise in transition from -15 to as high as 390 C. The amount of the increase was less for furnace cooled than for quenched material. The lowest transition found for recrystallized chromium, ICr-3, was 90 C[13], combining the more favorable conditions of fewer grains in the cross section[14], and slow cooling rate. This transition compares well with the <150 C tensile transition reported by Weaver[15] on annealed chromium containing 5 ppm nitrogen, 120 ppm oxygen, and 3 ppm carbon, with a grain size of 0.05 mm. The low transition of ICr-3 was apparently caused by localized yielding in grains up to 1 mm in diameter, sometimes occupying the entire specimen cross section. Material of similar purity, ICr-2, and annealing treatment but with a uniform grain size of 0.03 mm (1000 grains to the cross section) was apparently insensitive to localized yielding and gave a higher transition of 300 C.

One can speculate why the wrought condition had a lower transition. First, it has a higher dislocation density and a better probability of supplying unlocked dislocations for deformation. Second, the fibered structure is more conducive to ductility because of the greater difficulty in initiating fracture and propagating cleavage.

Fractures in brittle samples were almost completely transgranular, whereas severe distortion of the grains took place in ductile specimens.

As indicated in Figures 8 and 9, yield points were observed in wrought and recrystallized chromium above the transition. Their
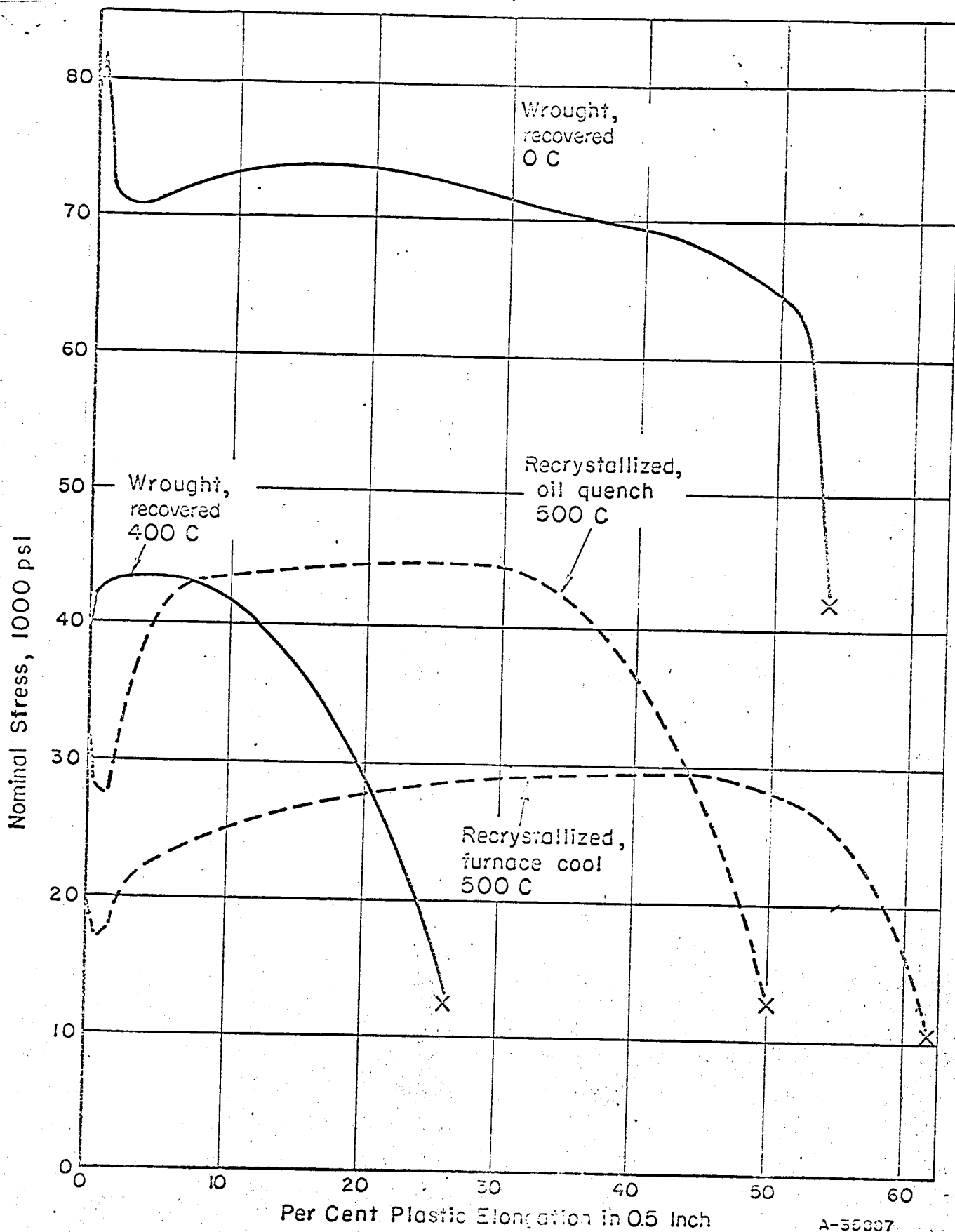
FIGURE 8.   STRESS-STRAIN CURVES OF UNALLOYED IODIDE CHROMIUM (ICr-2) AS AFFECTED BY
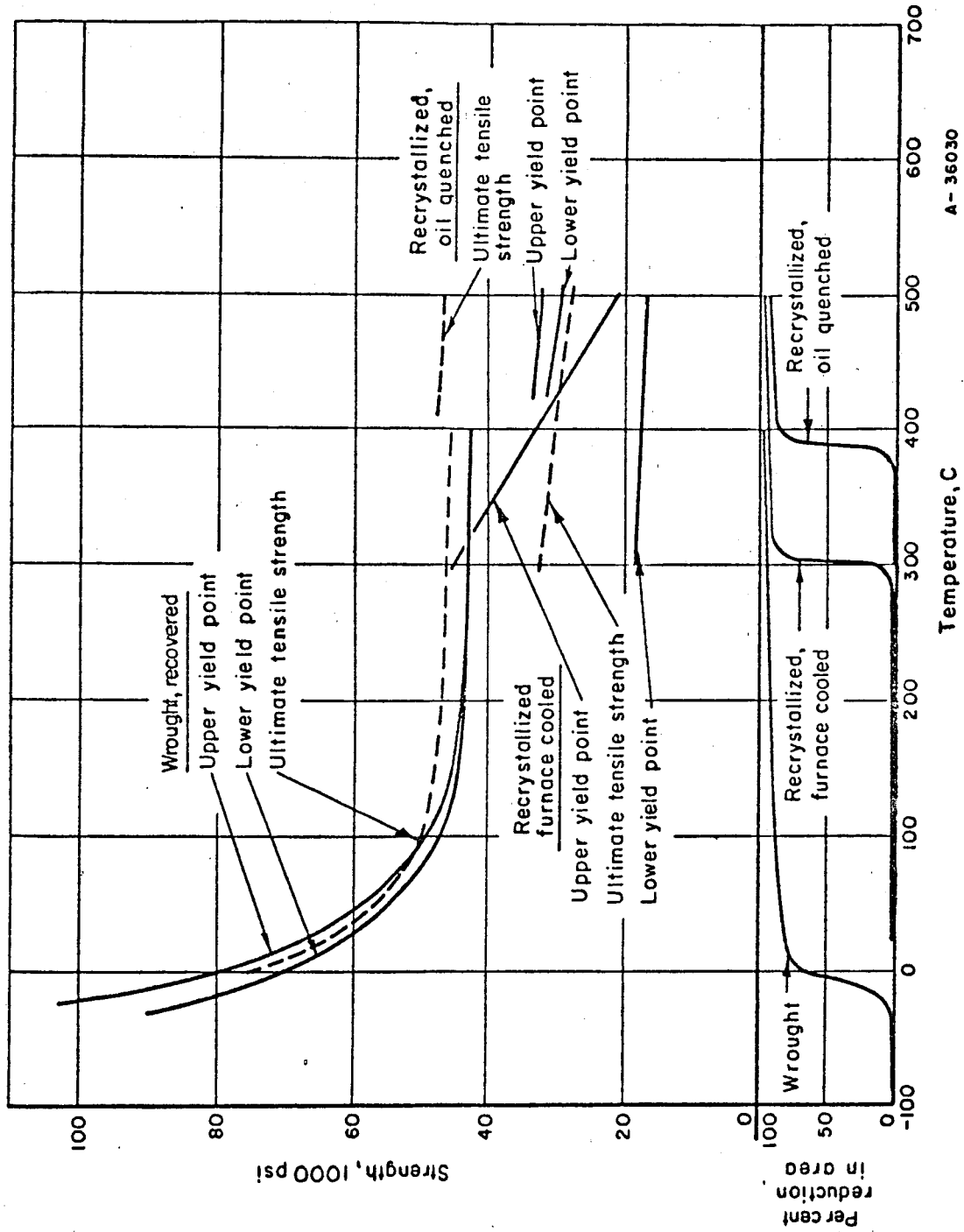STRUCTURE, HEAT TREATMENT, AND TEST TEMPERATURE

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FIGURE 9. TENSILE PROPERTIES OF UNALLOYED IODIDE CHROMIUM (ICr-2)

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presence and marked temperature dependence of yield strength are indicative of dislocation interaction with residual impurities. The magnitude of the yield point decreased with increasing temperature and eventually disappeared about 200 C above the transition. Yield points in recrystallized material were sharper than those in wrought.

Effect of Purity on Transition Behavior

The ductility of five chromium impurity alloys containing carbon, oxygen, nitrogen, and sulfur additions followed a pattern similar to that indicated for the unalloyed chromium in Figure 7. The results are summarized in terms of tensile transitions (to within about ±10 C) and are presented in Table 3 and Figure 10. To eliminate the grain size effect on transition caused by having under 100 grains to the specimen cross section[14], results for recrystallized ICr-3 and ICr-4 are not indicated in Figure 10. The data presented refer to fine-grained chromium with grain sizes averaging 0.01 to 0.03 mm (1000 to 10,000 to the cross section). Since this range apparently had little effect on the transition, Figure 10 indicates the relationship between transition, purity, and condition. It is evident that an increase in total interstitial content from 79 to 150-200 ppm caused marked increases in transition temperature, especially in the recrystallized condition. As was the case for unalloyed chromium, the recrystallized and quenched condition exhibited the highest transitions followed by the recrystallized and slow-cooled and then wrought and recovered conditions.

In the wrought condition, carbon and nitrogen raised the transition more than did oxygen or sulfur. Since oxygen has only a 10 ppm
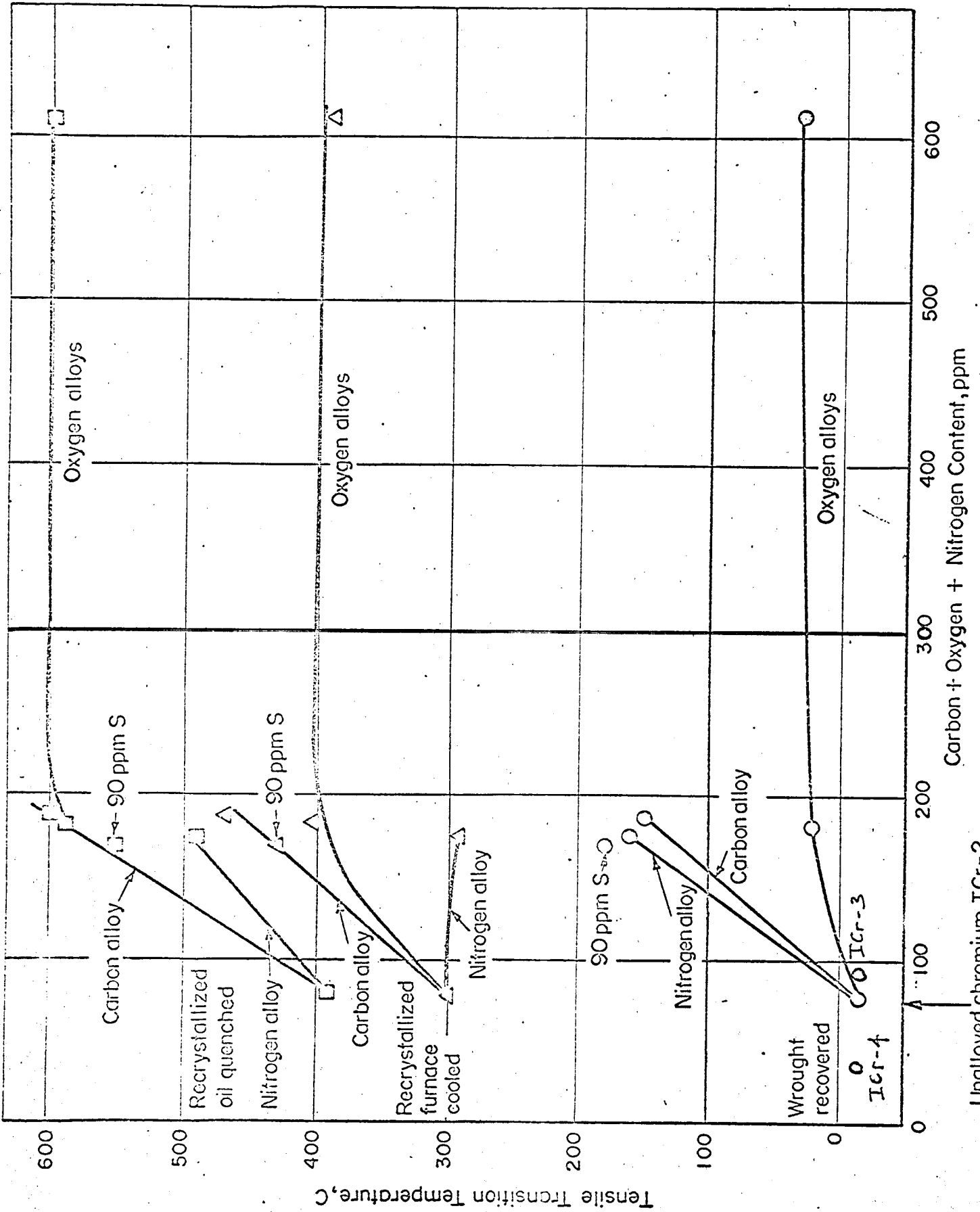
FIGURE 10. EFFECT OF CARBON, OXYGEN, NITROGEN, AND **SULFUR** ON THE TENSILE TRANSITION **TEMPERATURE** OF CHROMIUM

Grain size of recrystallized alloys was in the range 0.01 to 0.03 mm.

solubility in chromium at 1100 C[7], the major portion was in the form of a coarse oxide precipitate at room temperature. Increasing oxygen from 128 to 545 ppm apparently had little effect on the transition. Nitrogen[7] and carbon[16] are more soluble and would be expected to be more harmful to ductility. In the sulfur addition alloy, the transition temperature rise was probably caused by the high residual carbon, oxygen, and nitrogen which, together, amounted to a significant total of 170 ppm. Since the transitions of the sulfur, carbon, and nitrogen alloys were within the range of 150-180 C, the effect of sulfur is considered minor. It is worthy to note that the impurity alloys containing high carbon and nitrogen had the highest as-wrought hardnesses and the highest transitions.

In the recrystallized condition, interstitial impurity additions raised the transition of chromium by 90 to 210 C. Carbon and nitrogen again had the greatest effect while that of oxygen tended to saturate probably below 128 ppm. As was the case in wrought chromium, sulfur appeared to have little effect. The effects on tensile transition found for these four impurities are consistent with literature results. At similar levels, the detrimental effect of carbon[4,10,17] and nitrogen[1,3,4,12,15,18] and relatively small effect of oxygen[1,4,10,12] and sulfur[4] on the bend and tensile ductility of chromium have been reported.

As was the case for unalloyed chromium, quenching caused a higher transition in recrystallized material than did slow cooling. These and previous results suggest the transition of chromium is not only dependent on the total interstitial content but also its distribution.

Slow cooling with adequate time for diffusion can result in coarse precipitates which can form internal notches and raise the transition. On the other hand, quenching allows little time for diffusion. Therefore, at room temperature most of the interstitials soluble or present during annealing at 1100 C would be either in supersaturated solid solution or in the form of fine precipitates. This distribution of interstitials seems to be more harmful to ductility than one of coarse precipitates. Most of the oxygen in the alloys containing 128 and 545 ppm was insoluble at the annealing temperature. Since the transitions of both alloys were similar, the massive rounded insoluble oxide phase apparently had little effect on ductility.

Above the transition, yield points and high ductilities were found in all the impurity alloys and unalloyed chromium, as indicated in Table 4. The wrought condition had the highest strength and lowest strain hardening exponent. The recrystallized slow-cooled condition had the lowest strengths and highest strain hardening. Evidence of discontinuous yielding was noted in the recrystallized and quenched alloys and one unalloyed chromium specimen (ICr-2 tested at 400 C). This behavior is suggestive of strain aging which has been reported by others[15,19,20].

TABLE 4.   TENSILE PROPERTIES OF CHROMIUM ABOVE THE TRANSITION TEMPERATURE
AS AFFECTED BY PURITY AND HEAT TREATMENT

Alloy	Temperature, C	Upper Yield Point, 1000 psi	Lower Yield Point, 1000 psi	Ultimate Tensile Strength, 1000 psi	Plastic Elongation in 1/2 Inch, per cent	Reduction in Area, per cent	Strain-Hardening Exponent
			Wrought, Recovered 1 Hour at 800 C, Furnace Cooled				
ICr-2	25	65.5	58.4	64.2	56.6	78.6	0.12
ICr-2	200	43.9	43.9	47.6	36.0	90.2	0.07
ICr-4	25	62.6	54.1	60.1	43.8	68.4	0.08
ICr-4	200	40.9	40.4	45.1	36.0	86.5	0.07
C-1	200	64.2	63.5	63.5	24.0	82.8	0.03
O-1	200	57.4	55.0	56.2	28.6	86.9	0.04
O-2	200	51.0	49.9	52.5	32.2	78.4	0.08
N-3	210	38.2	38.2	42.1	26.6	86.3	0.07
S-1	200	67.6	62.0	62.6	17.7	69.3	0.04
			Recrystallized 1 Hour at 1100 C, Oil Quenched				
ICr-2	500	31.8	27.5	44.6	49.8	93.3	0.30
ICr-4	350	32.0	30.3	40.0	29.0	89.2	0.12
C-1	610	21.0	21.0	37.5	63.6	91.1	0.22
O-1	600	31.2	26.7	40.9	55.6	91.3	0.23
O-2	600	29.7	25.3	38.7	61.3	87.5	0.23
N-3	500	46.8	32.1	59.1	35.6	88.5	0.26
S-1	580	18.2	18.2	39.0	54.8	92.4	0.22
			Recrystallized 1 Hour at 1100 C, Furnace Cooled				
ICr-2	400	32.7	19.2	30.4	72.4	95.3	0.41
ICr-2	500	19.9	16.9	29.3	61.8	93.2	0.28
ICr-4	230	23.4	14.9	29.4	41.6	90.0	0.28
C-1	500	25.7	22.9	34.7	52.6	92.9	0.23
O-1	400	30.1	20.7	31.9	76.6	92.5	0.30
O-2	400	27.8	20.0	32.2	69.2	90.3	0.29
N-3	400	15.4	14.1	31.1	52.0	86.8	0.24
S-1	450	16.3	14.2	35.7	59.8	69.8	0.28

Conclusions

(1) Nitrogen is the most effective interstitial in quench hardening
of chromium in the investigated range of 10-360 ppm.

(2) The recrystallization temperature of chromium with 80 per cent
warm work at 900 C is about 975 C. Up to about 100 ppm oxygen,
nitrogen, and sulfur have little effect and carbon raises it by
50 C.

(3) The transition temperature of wrought and recovered iodide
chromium with 39 to 95 ppm total interstitials is -15 C.

(4) Recrystallizing at 1100 C causes the transition to rise to
90-390 C depending on the grain size, purity, and cooling rate.

(5) At about the 100 ppm level carbon, oxygen, and nitrogen raise
the transition of wrought chromium to 20-180 C whereas sulfur
has almost no effect. Increasing the oxygen level to 545 ppm
has little additional effect.

(6) At about the 100 ppm level carbon, oxygen, and nitrogen raise
the transition of recrystallized chromium to 490-600 C.
Additional oxygen up to 545 ppm has little effect.

(7) Recrystallized and quenched chromium has a higher transition
than recrystallized and slow-cooled material, presumably
because of the finer distribution of interstitials.

(8) Ductile chromium exhibits yield points characteristic of
dislocation interaction with interstitials.

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